Evaluation of the Grounding Circuit Measurements for Stator Ground-Fault Location of Synchronous Generators

F. R. Blánquez, E. Rebollo, and C. A. Platero

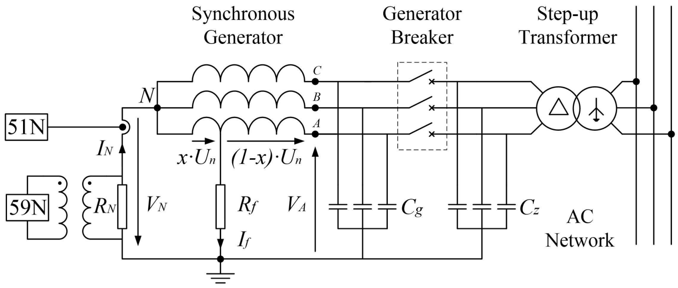

Fig. 1. Simplified scheme of a power plant with a synchronous generator grounded through a high-value resistance

I. Introduction

In power plants, protective systems are vital not only to guarantee the safety of the personal and minimize the damage on the power components and equipment during many kind of events, but also to maintain the reliability of the power system.

One of the most common defect of power synchronous generators is the stator-winding ground fault [1]. The consequences of stator ground faults depends radically on the generator grounding scheme [2]. If the generator is grounded through a high-value impedance the circulating current during this defect is limited by this impedance, but, in case of low impedance grounding, this current may be very high, depending on the location of the fault [3]. In this latter type of grounding scheme the damage caused by a solid ground fault at the generator terminal could be very severe, since the stator winding is short-circuited solidly [4].

Typically, high-power synchronous generators are grounded through a high impedance, whose value is generally set in order to limit the neutral current in case of solid ground-fault at the generator terminal to 5 A or 10 A [5]. The most basic stator ground-fault protection scheme is based on the measurement of the neutral voltage (59N) [6] or the neutral current (51N) [7]. Since stator ground faults cause the appearance of a neutral circulating current (and therefore a neutral voltage), any ground fault may be detected by the measurement of any of these variables [8]. But the setting of the trip threshold to zero is not recommended for this scheme, since the presence of any transient neutral current may cause an unwanted trip command. This kind of protection scheme is generally called 95% stator ground-fault protection, due to the portion of the stator winding that they protect.

The aforementioned systems allow detecting stator ground faults, but the location of the ground fault is still unsolved. As the equivalent resistance of the breakdown channel (fault resistance) is unknown, determining the exact location of the ground-fault is impossible. In this paper, the measurements provided by the grounding circuit are evaluated in order to obtain information about the fault location.

This paper is structured as follows. First, the theoretical approach of ground-fault location in stator windings is described in Section II. Then, the use of 59N/51N is discussed as way of detecting the stator phase under faulty conditions, and as a first estimation of the ground fault, in in Section III. In section IV, the results of estimating the ground-fault location using real data are shown and discussed. Finally, in Section V the laboratory tests are described to show an example of practical application of this method and the validity of the results.

II. Theoretical Approach of Ground-Fault Location in Stator Windings

In synchronous generators grounded through a high-value impedance, the stator ground faults are generally detected using a neutral overvoltage protection (59N) or neutral overcurrent protection (51N). In Fig. 1, the simplified scheme of a power plant is shown, where the general scheme of 59N and 51N are represented. In this figure, a ground-fault is

F. R. Blánquez, E. Rebollo and C. A. Platero are with the Electrical Engineering Department of the Universidad Politécnica de Madrid (Spain), (E-mail: fr.blanquez@gmail.com).

represented in phase A, where R_f is the fault resistance, I_f is the fault current, U_n is the generator phase voltage, and x represents the exact location of the ground fault, from 0 (Neutral, N), to 1 (terminal, A). This ground fault causes the appearance of a Neutral Voltage (V_N), and a circulating Neutral Current (I_N), which are measured by the described protections. In high-power generators, several capacitances to ground have to be taken into account, such as the equivalent capacitance to ground of the stator winding, C_g, or the capacitance to ground of the generator breaker, the GSU transformer, the auxiliary transformer and the leads, among some others, all included in C_z.

In real installations, the measurements of this scheme that can be obtained include I_N, V_N, U_n and V_A, the terminal voltage. R_N is the grounding resistance, whose value is typically obtained as the resistance needed to limit the circulating current in case of a solid ground-fault at the generator terminal to 10 A (5 A is also used). According to this, a ground fault is detected when the value of I_N is above the 51N setting threshold (whose value is generally set to 5% of 10A), or the value of V_N is above the 59N setting threshold (whose value is generally set to 5% of U_n), in order to protect approximately the upper 95% of the stator winding. Lower setting level is not recommended due to the possibility of unwanted trip commands.

The equivalent circuit of the grounding network for zero sequence component in case of ground-fault is shown in Fig. 2, where C_T represents the total capacitance of the power system (1).

$$C_T = C_g + C_z \tag{1}$$

In this circuit, the parameters of the elements of the left hand side branch are unknown, however I_f [3] can be expressed by (2).

$$\underline{I}_f = \underline{U}_n \cdot x \cdot \frac{1 + j\omega C_T R_N}{R_f(1 + j\omega C_T R_N) + R_N} \tag{2}$$

Since $\underline{I}_N$ is measured, (2) can be expressed as (3)

$$x \cdot \underline{U}_n = \underline{I}_N (R_N + R_f(1 + j\omega C_T R_N)) \tag{3}$$

where the underline means phasor magnitude, ω is (4) and f is the fundamental frequency (50 Hz or 60 Hz) for this grounding network.

$$\omega = 2 \cdot \pi \cdot f \tag{4}$$

The expression (3) provides the first relation between x and R_f, and some information can be extracted related to the fault location.

III. Utilization of the Grounding Circuit Measurements in the Ground-Fault Location

First, lets consider the current through the capacitive branch as zero, which means there is no capacitance to ground. This fact is very close to be realistic for lower values of C_T, since it will be described later. This consideration leads to expression (5)

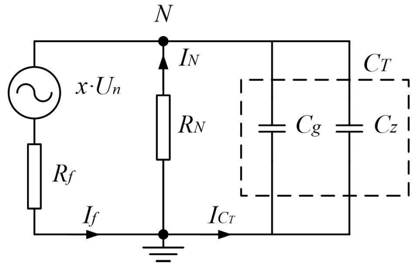

Fig. 2. Equivalent circuit of the fundamental frequency grounding network for zero sequence component.

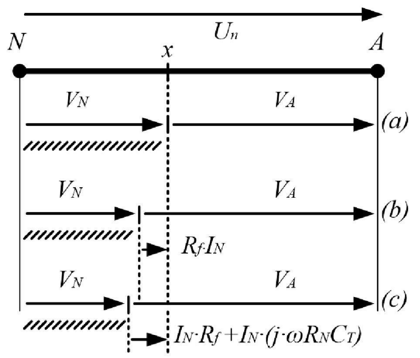

Fig. 3. Representation of the amplitude of the neutral voltage and terminal voltage in case of (a) without the effect of C_T and with R_f = 0; (b) without the effect of C_T and with $R_f \neq 0$; (c) considering the effect of C_T and with $R_f \neq 0$.

$$x \cdot U_n \approx I_N (R_N + R_f) \tag{5}$$

According to this, in case of a stator-ground fault with no fault resistance, the fault location can be directly obtained as the ratio between V_N and U_n (6) (see Fig. 3 (a)).

$$x_0^* = \frac{I_N \cdot R_N}{U_n} = \frac{V_N}{U_n} \tag{6}$$

where x_0^* is the first estimation of the ground-fault location using only the information of 59N or 51N. As the value of the fault resistance increases, this estimation becomes imprecise (Fig. 3 (b)). Moreover, if capacitances to ground are considered, the use of this ratio as the fault location is more inaccurate (Fig. 3 (c)).

Besides the fact that this first estimation is not accurate for high-value of fault resistance, it may be useful for the location of solid ground-fault. The main problem is that, unfortunately, the value of the fault resistance is unknown, and this fact makes this estimation unreliable. However, expression (3) provide relevant information since, in case of having a way of estimating the value of R_f, the value of x may be also estimated more accurately.

But, this first relation provides relevant information regarding the faulty phase of the stator winding. Due to the fact that, in case of ground-fault, the phase angle between the neutral voltage and the terminal voltage of the faulty phase is very close to zero, the phase winding under faulty condition can be detected. For instance, in Fig. 1, V_N and V_A are almost in

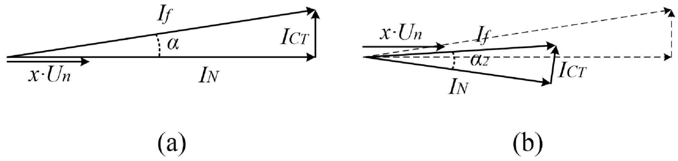

Fig. 4. (a) (b) Phasor diagram of the current in the grounding circuit at fundamental frequency. (a) R_f = 0 Ω. (b) $R_f > 0$ Ω.

phase. Moreover, the ratio x_0^* allows obtaining an estimated portion of the stator winding which is free of ground-fault (portion of the winding shadowed in Fig. 3 in every case). The real portion of the stator winding from the neutral point (N) to the fault point (x), may be larger than the portion estimated, but it can help in the process of the physical location of the ground-fault, considering that in many cases the value of R_f is very small.

A. Error caused by the Utilization of x_0^* as a Fault Locator.

In Fig. 4 the phasor diagram of the currents in the grounding circuit at fundamental frequency is shown, where I_{C_T} represents the capacitive current. In case if R_f = 0 Ω (Fig. 4 (a)) the neutral current and the phase voltage under faulty condition have the same phase angle. In case of ground fault with $R_f >$ 0 Ω (Fig. 4 (b)) at the same point of the winding, the neutral current is reduced in magnitude and phase shifted. The use of x_0^* as a stator-winding ground-fault locator implies neglecting the effect of the capacitance to ground of the stator winding and the fault resistance. This assumption cause a ground-fault location error (E_T) which can be expressed as:

$$E_T = x - x_0^* = x \cdot \left(1 - \frac{R_N}{\sqrt{(R_N + R_f)^2 + (\omega C_T R_N R_f)^2}}\right) \tag{7}$$

This total error is composed by the addition of the error related to neglecting R_f (E_1), and the error related to neglecting the effect of C_T (E_2). In this way,

$$E_T = E_1 + E_2 \tag{8}$$

where E_2 is expressed as

$$E_2 = x \cdot \left(1 - \frac{R_N + R_f}{\sqrt{(R_N + R_f)^2 + (\omega C_T R_N R_f)^2}}\right) \tag{9}$$

IV. Results of Simulation of Stator Ground-Fault Location

In order to evaluate this locating estimation, the real data, summarized in Table V, has been used. Firstly, in Fig. 5 the fault-location estimation (x_0^*) for $x \in$ [0,1] and $R_f \in$ [0,1000] Ω is represented. Moreover, the module of the neutral current is also shown, where the maximum value (10 A in this case) is obtained in a ground fault at phase terminal (x = 1) with R_f = 0 Ω. As observed, as the fault resistance increases, the value of x_0^* decreases, and the fault location is more inaccurate. The total error in the fault-location estimation

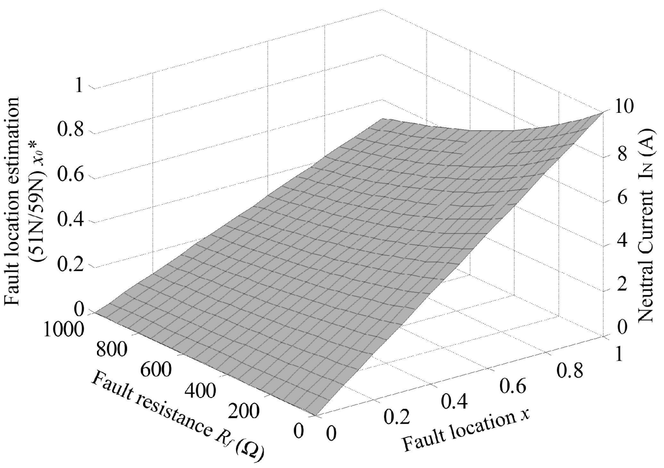

Fig. 5. Fault location estimation through x_0^* and neutral current (I_N) for $x \in$ [0,1] and $R_f \in$ [0,1000] Ω.

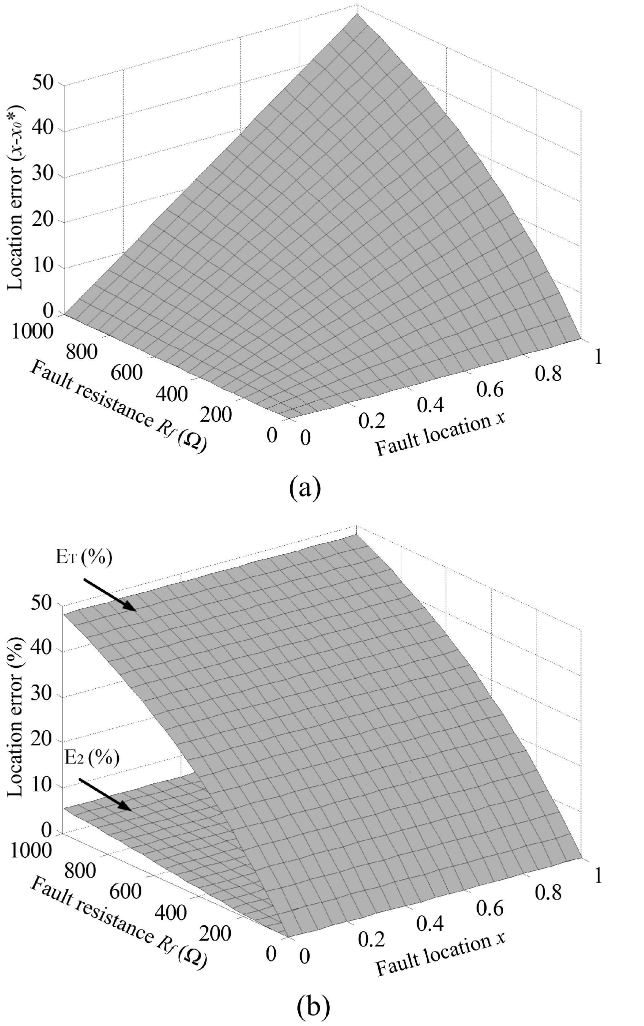

Fig. 6. (a) Absolute location error (x_0^*-x); (b) Relative total location error (E_T (%)) and relative location error added by neglecting the stator capacitance to ground (E_2 (%). $x \in$ [0,1] and $R_f \in$ [0,1000] Ω.

added is shown in Fig 6 (a). As shown, as the ground fault is closer to the generator terminal the total error is increased.

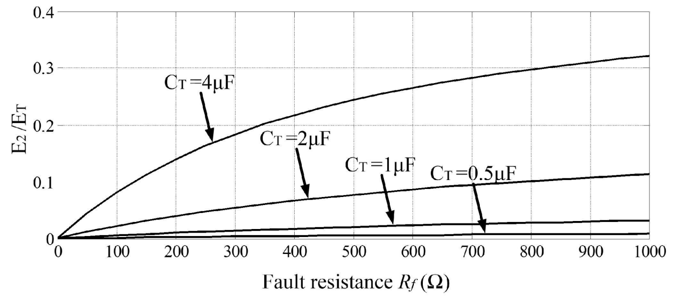

Fig. 7. Ratio E_2/E_T for $R_f \in$ [0,1000] Ω and several values of stator capacitance to ground..

Since the utilization of x_0^* as a fault locator implies neglecting the existence of the stator capacitance to ground and the fault resistance, the study of the error related to each parameter is important. In Fig. 6 (b) shows the total relative error (E_T) and the relative error related to neglecting exclusively the effect of C_T (E_2) for $x \in$ [0,1] and $R_f \in$ [0,1000] Ω. As observed, E_2 represents an small part of the total error of this fault location. The ratio between E_2 and E_T depends radically on the value of the stator capacitance to ground. Fig. 7 shows the value of this ratio for several values of capacitance and for [0,1000] Ω. For values of capacitance lower than 4 μF, the value of this ratio is under 0.3, even for R_f = 1000 Ω. This fact shows that ignoring the value of the fault resistance is the most relevant term of the total error. Although the value of total capacitance to ground can be higher of 4 μF, it is not common, and values like 2μF are, actually, considerably high.

Table I and Table II summarized the value of I_N, V_N, x_0^*, E_T for $x \in$ [0,1] in case of R_f = 100 Ω and R_f = 1000 Ω, respectively. As shown, the fault location in case of a ground-fault with R_f = 1000 Ω is less accurate than in case of R_f = 100 Ω. Second, the estimation is less accurate as the fault location increases. According to this, the highest error is observed for ground faults at the generator terminal in both cases (Table I and Table II). This fact is explained as expression (9) depends on the I_N or V_N, which become very small when the fault is located closer to the neutral. In Table III and Table IV, the effect of the fault resistance in the estimation on the fault location. As described, through the comparison of both tables, it can be observed that the estimations in case of a ground fault at x = 0.25 are more accurate than faults located at x = 0.75. However, in both cases the accuracy is reduced as the fault resistance is increased, as expected. Finally, the estimation of both variables is very accurate in the range from 0 Ω to 100 Ω, but if the fault resistance has a higher value, the estimation may be very harmed.

V. Conclusions

In this paper the grounding circuit measurements are evaluated in order to provide information about the ground-fault location in stator winding of synchronous machines. This estimation using 59N/51N is discussed, concluding that the ground fault can not be accurately located through the available measurements in the 95% stator ground-fault protection scheme.

TABLE I
Grounding Circuit Measurements and results of Estimation of Ground-Fault Location for R_f = 100 Ω.

x [%]	I_N [A]	V_N [V]	x_0^* [%]	x-x_0^* [%]
0.00	0.00	0	0.00	0.00
10.00	0.92	1,115.0	9.23	0.77
20.00	1.85	2,242.2	18.45	1.54
30.00	2.77	3,357.2	27.68	2.32
40.00	3.69	4,472.3	36.90	3.10
50.00	4.61	5,587.3	46.12	3.87
60.00	5.54	6,714.5	55.35	4.65
70.00	6.46	7,829.5	64.58	5.42
80.00	7.38	8,944.6	73.80	6.20
90.00	8.30	10,059.6	83.03	6.97
100.00	9.23	11,186.8	92.26	7.74

TABLE II
Grounding Circuit Measurements and results of Estimation of Ground-Fault Location for R_f = 1000 Ω.

x [%]	I_N [A]	V_N [V]	x_0^* [%]	x-x_0^* [%]
0.00	0.00	0.0	0.00	0.00
10.00	0.52	630.2	5.18	4.82
20.00	1.04	1,260.5	10.37	9.63
30.00	1.55	1,878.6	15.55	14.45
40.00	2.07	2,508.8	20.73	19.27
50.00	2.59	3,139.1	25.91	24.09
60.00	3.11	3,769.3	31.10	28.90
70.00	3.63	4,399.6	36.28	33.72
80.00	4.15	5,029.8	41.46	38.54
90.00	4.66	5,647.9	46.64	43.36
100.00	5.18	6,278.2	51.83	48.17

TABLE III
Grounding Circuit Measurements and results of Estimation of Ground-Fault Location for x = 0.25.

R_f [Ω]	I_N [A]	V_N [V]	x_0^* [%]	x-x_0^* [%]
0	2.50	3,031.1	25.00	0.00
20	2.46	2,982.6	24.60	0.40
100	2.31	2,800.7	23.18	1.82
250	2.06	2,497.6	20.60	4.40
500	1.77	2,133.9	17.74	7.40
750	1.55	1,794.4	15.46	10.20
1000	1.35	1,636.8	13.70	11.50

TABLE IV
Grounding Circuit Measurements and results of Estimation of Ground-Fault Location for x = 0.75.

R_f [Ω]	I_N [A]	V_N [V]	x_0^* [%]	x-x_0^* [%]
0	7.50	9093.3	75.00	0.00
20	7.38	8947.8	73.80	1.20
100	6.94	8414.3	69.36	5.64
250	6.22	7541.4	62.22	12.78
500	5.31	6438.1	53.08	21.92
750	4.63	5613.6	46.27	28.73
1000	4.10	4971.0	41.00	34.00

However, the ratio between the neutral voltage and the phase voltage provide a portion of the winding that is certainly free of faults. Although, the part of the winding from the neutral to the exact point of the ground fault may be longer than this first estimation, this information could help to locate physically the defect in the repairing process.

The total error in locating the ground fault is mainly due to the effect of ignoring the fault resistance, since the error added by neglecting the stator capacitance. Moreover, this total error increases as the fault resistance increases and as the fault location is closer to the phase terminal.

Finally, the relation between the fault location and the fault resistance obtained of the zero sequence grounding network implies the first expression of a possible estimation algorithm, since, in case of estimating the value of the fault resistance by any method, the location of the ground fault may be estimated more accurately. Further research of this study will focus on this point.

APPENDIX

TABLE V
CIRCUIT PARAMETERS OF A REAL INSTALLATION FOR THE STUDY OF THE STATOR GROUND-FAULT LOCATION ALGORITHM

Generator rated voltage	U_r	$21\ kV$
Generator phase voltage	U_n	$21/\sqrt{3}\ kV$
Grounding resistance	R_N	$1212\ \Omega$
Total capacitance to ground	C_T	$2\ \mu F$
Maximum neutral current	I_{Nmax}	$10\ A$

ACKNOWLEDGMENT

The authors wish to acknowledge the technical support of Araceli Monje and Raphael Grollemund from Schneider Electric.